International Journal of GEOMATE, Jan., 2021, Vol.20, Issue 77, pp. 33-39
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.77.62979
Geotechnique, Construction Materials and Environment

THE RESULTS OF OBSERVING THE SEISMOELECTRIC EFFECT IN A GAS CONDENSATE HYDROCARBON FIELD USING A SOURCE OF SEISMIC FIELD

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ABSTRACT: The main purpose of this study is to experimentally confirm the possibility of recording seismoelectric effects at the Bystryanskaya gas condensate field (Krasnoyarsk Territory, Russia) using nonexplosive sources of a seismic field. This work analyses the current state of research in the field of recording various manifestations of seismoelectric effects in the search for hydrocarbons, as well as gives a theoretical assessment of the electromagnetic field created by a sheet deposit affected by a seismic impact, which shows that to register this field, it is necessary to use special methods of increasing the final signal-to-noise value for the recorded information parameter. The results of the experiment conducted on this field in 2019 with the use of a nonexplosive wheeled EM-source – seismic vibrator “KEM-4” – showed that accumulation along 72 measurements (3 sessions of 24 sensors each) made it possible to record the seismoelectric effect over the sheet deposit located at a depth of about 2,000 m. Thus, the results obtained in the work show that the regression of seismic effects using the accumulation of the signal at the seismic station gives the signal-to-noise ratio of the correlation function equal to approximately 3.

Keywords: Seismic Exploration, Electrical Exploration, Electroacoustics, Seismoelectric Effect, Petroleum

1. INTRODUCTION

The practices of geophysical exploration in the search for oil and gas have proved the efficiency of integrated use of seismic and electrical exploration methods. This integration, however, occurs directly in the process of interpreting geophysical data. This approach neglects the fact that the combined data are non-uniformly scaled, and does not take into account the mutual influence of fields of different physical nature on each other. The application of this approach depresses the opportunity to obtain complete and more reliable information on the petrophysical properties of rocks, in particular, rocks that make up the upper part of the section [1-6].

The seismoelectric effect (SEE) was discovered experimentally by A. G. Ivanov in 1939 [1]. The theory is based on the works of Ya. I. Frenkel and M. Biot [2,3], and was further developed by S. Pride and M. Haartsen [4,5]. According to their works, determining electromagnetic and elastic fields of the SEE is reduced to solving a problem which takes into account the mutual influence of elastic and electromagnetic fields. M. Biot's model is a high-frequency one, which is not in line with the elastic wave sources used in ground geophysics. B.S. Svetov and V.P. Gubatenko [6] in 1999 were able to develop a low-frequency mathematical model of the SEE which was based on the sequential solving of problems of the theory of elasticity of a continuum, fluid dynamics, electrokinetics and electrodynamics. This approach greatly simplifies the calculation of the electromagnetic field in the low-frequency approximation due to the fact that turns out to be possible to neglect the inverse effect of the physical fields, generated in this chain, at low frequencies. Unlike in the high-frequency models of Ya. I. Frenkel and S. Pride-M. Haartsen, it corresponds to the low-frequency spectrum of frequencies (1-100 Hz) used in ground geophysical techniques [7,8]. In 2015, various authors developed a mathematical model of the SEE of the 2nd kind, caused by plane elastic waves in porous moisture-saturated media. The mechanism leading to the emergence of an electric field in rocks experiencing elastic deformations has been known for a long time and is described in the framework of the Helmholtz–Smoluchowski equation combined with Biot theory of a fluid-saturated poroelastic medium [9].

In [10], the authors consider a technique for searching for fluid-containing underground formations (hydrocarbon deposits), which bases on generating seismic vibrations followed by recording the electromagnetic field in the frequency range of

0 – 30 Hz by means of a magnetic antenna. It is indicated that the electromagnetic field is recorded from several tens of seconds to a minute after a seismic excitation. According to the authors in [10], this technique allows recording electrokinetic seismic phenomena, i.e. the appearance of an electromagnetic field induced by a pulsed seismic impact.

The authors in [11] propose a similar technique for searching for hydrocarbons using the above measurement scheme in the frequency range of 0.1–20 Hz. This work emphasizes that this method allows estimating the depth of producing formations. The works [12,13] give data on shelf hydrocarbon exploration technique based on a simultaneous recording of microseismic vibrations in 0.008–20Hz frequency range and an electromagnetic field (E and H components) in the frequency range of 0.1–100 Hz. Additionally, they measured acoustic noise (5 – 50,000 Hz), hydrodynamic (0.01 – 100 Hz), etc., followed by digital filtering and factor analysis. In [13], it is also proposed to record the pressure created during the passage of a tsunami at frequencies of 0.003 – 0.01 Hz. [14] suggests a passive method for recording seismoelectric effects with simultaneous recording of the Earth's seismic and electromagnetic noise over a hydrocarbon field with the subsequent calculation of the maximum of a correlation function.

Despite the progress which has been achieved in the recent decades in understanding the seismoelectric processes [15-17], these phenomena are poorly used in practical geophysics due to the difficulty of recording the corresponding fields and subsequent interpretation of the results. At the same time, technologies based on these phenomena may have a certain potential as a source for obtaining additional geophysical information about the studied environment.

The relevance of the seismoelectric (SE) methods is also driven due to the presence of experimental material [18,19] which indicates the existence of a correlation between natural signals of seismic and electromagnetic origins in hydrocarbon deposit containment areas. In a broader sense, the relevance of research is determined by the need for an objective analysis of the capabilities of the passive SE method for mapping oil-and-gas pools and determining their parameters. Previously, it was experimentally showed in [20,21] that it is possible to increase the geophysical data completeness by complex perturbing of the initial state of the geological rocks with elastic and electromagnetic fields.

2. METHODS AND MATERIALS

The SE method involves determining the maximum of the function of cross-correlation between seismic and electromagnetic fields. For sensitivity analysis, an estimate of the pressure created by the seismic field non-explosive source KEM-4 is given below, which will enable determining whether it is possible to apply the SE method onshore. The seismic vibrator "Yenisei KEM-4" had got the following parameters: impact force $F=10^5$ H; weight of the striker plate (consists of 4 elements) $m_{pl}=25\ 000 \cdot 4=100\ 000$ kg; area of each plate element $S=0.5$ m^2, total area S=0.5·4=2 m^2; excitation pulse duration $\tau=7\cdot10^{-3}$ sec; density of the medium $\rho=2\cdot10^3$–$3\cdot10^3$ kg/m^3; P-wave velocity in the medium $V_p=4\cdot10^3$ m/sec; the frequency at which the profile is excited $f_a=100$ Hz. The formation parameters: dimensions $L=2000\times2000$ m, formation thickness $d=100$ m; depth of the formation $r=2000$ m.

Determine the pressure on the formation which is created by the source by means of using the classical relationships of frequency f_a, soil displacement amplitude A_0, and wave propagation velocity V_a. For distance r, the pressure amplitude equals [7]:

$$P = A_0\,\omega_a\,\rho V_p\,, \qquad (1)$$

where A_0 is an amplitude of soil displacement in a seismic wave, $\omega_a = 2\cdot\pi\cdot f_a$.

Directly below the plate, the soil displacement amplitude is defined as [8]:

$$A_0 = \frac{F\cdot\tau^2}{2m}, \qquad (2)$$

where $m=m_{pl}+m_s$ is a sum of the plate mass m_{pl} and the added mass of soil m_s which depends on the density of soil and the size of the plate. The depth of the zone of adjoined soil is $H=(2–2.5)*d$; d is an effective diameter of the baseplate; $m_s=282$ kg; $A_0=7.83\cdot10^{-5}$ m; the pressure under the plate is $P_0=A_0\cdot\omega_a\cdot\rho\cdot V_p=4\cdot10^5$ Pa.

The amplitude of soil displacement near the formation for $r=2000$ m at the attenuation coefficient of $\alpha=2\cdot10^{-4}$ 1/m [7]:

$$A = \frac{A_0}{\left(\frac{\omega_a}{V_p} r\right)^{1/2}} e^{-\alpha r} = 3.62\cdot10^{-6}\ m \qquad (3)$$

It should be taken into account that only a 0.1 part of the impact force goes into the compressional P-waves, then the pressure amplitude near the formation is [7,8]:

$$P = A\omega_a \rho V_p \cdot 0.1 = 1.82 \cdot 10^4 \ Pa \quad (4)$$

The authors in [17] consider a model of the behaviour of a productive formation under pressure. According to this model, the formation is a set of elementary electric dipoles located over the entire area of the formation, the length of these dipoles changes under pressure, and, therefore, each of them creates its own electric field. In a quasi-stationary approximation, the maximum of the electric field of the formation on the surface equals:

$$E_x = dE_x \cdot \Phi_{max}, \quad (5)$$

where, dEx is a coefficient dependent on the thickness of the formation and its electrodynamic parameters, and the pressure of elastic waves on the formation; Φ_{max} is a geometrical multiplier which takes into consideration the location of all the dipoles.

Given that the formation lies at a depth of r=2000 m, and its thickness is 100 m: $dE_x = 2.15 \cdot 10^{-9}$; $\Phi_{max} = 2.2 \cdot 10^{-4}$; the maximum value of the electric field of the formation at the surface $E_x = dE_x \cdot \Phi_{max} = 5 \cdot 10^{-13}$ V/m. According to this model, the maximum of the electric field of the formation is observed in the zone of the edge of the pool.

Assess the level of pressure at the surface level, which a vibrating formation creates. Suppose that a seismic wave of the Yenisei KEM-4 source falls on the formation normally and is completely reflected. The amplitude of soil displacement on the surface will be as follows [7]:

$$A_s = \frac{A}{\left(\frac{\omega_a}{V_p} r\right)^{1/2}} e^{-\alpha r} = 1{,}67 \cdot 10^{-7} \ m \ , \quad (6)$$

where A=3.62·10^{-6} m is the amplitude of soil displacement on the formation surface. Displacement A_s creates pressure $P_s = A_s \cdot \omega_a \cdot \rho \cdot V_p$=840 Pa.

Thus, the above theoretical estimates when setting the onshore SE method show that the electric field created by a hydrocarbon pool on the Earth's surface under the impact of a seismic wave can only be detected only by means of using special methods to increase the signal-to-noise ratio, in this case, the problem can be solved at the expense of the accumulating and averaging of the obtained parameters, which ultimately will allow raising the overall signal-to-noise ratio for the information parameter.

As it has been indicated above, the authors of this article have already published the results of observations of the SEE in the gas condensate field (Bystryanskaya gas condensate field, Krasnoyarsk Territory) in 2017 [21]. In July 2019, the measuring was repeated to confirm the obtained data. Excitation of the geological environment was carried out by the specialized seismic source "Yenisei KEM-4" (with the impact force of 10·10^5 H).

Fig.1 shows a map of Bystryanskaya gas condensate field with measurement points plotted on it in 2019, and the assumed field boundaries at different depths according to exploratory drilling.

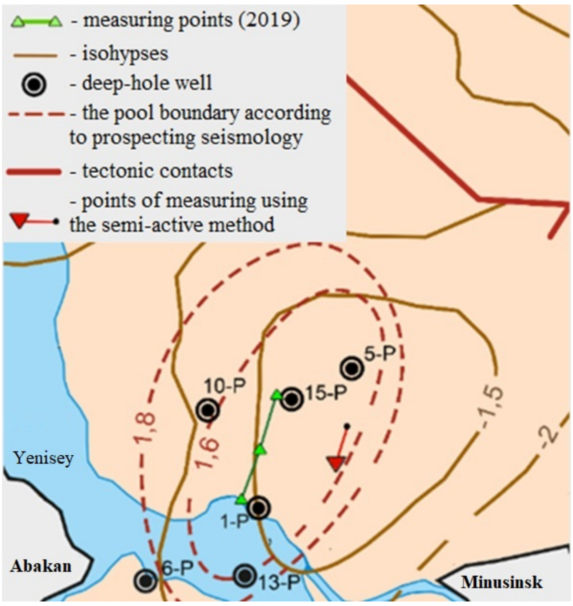

Fig.1 The profile of observation by standard prospecting seismology and passive seismoelectric method

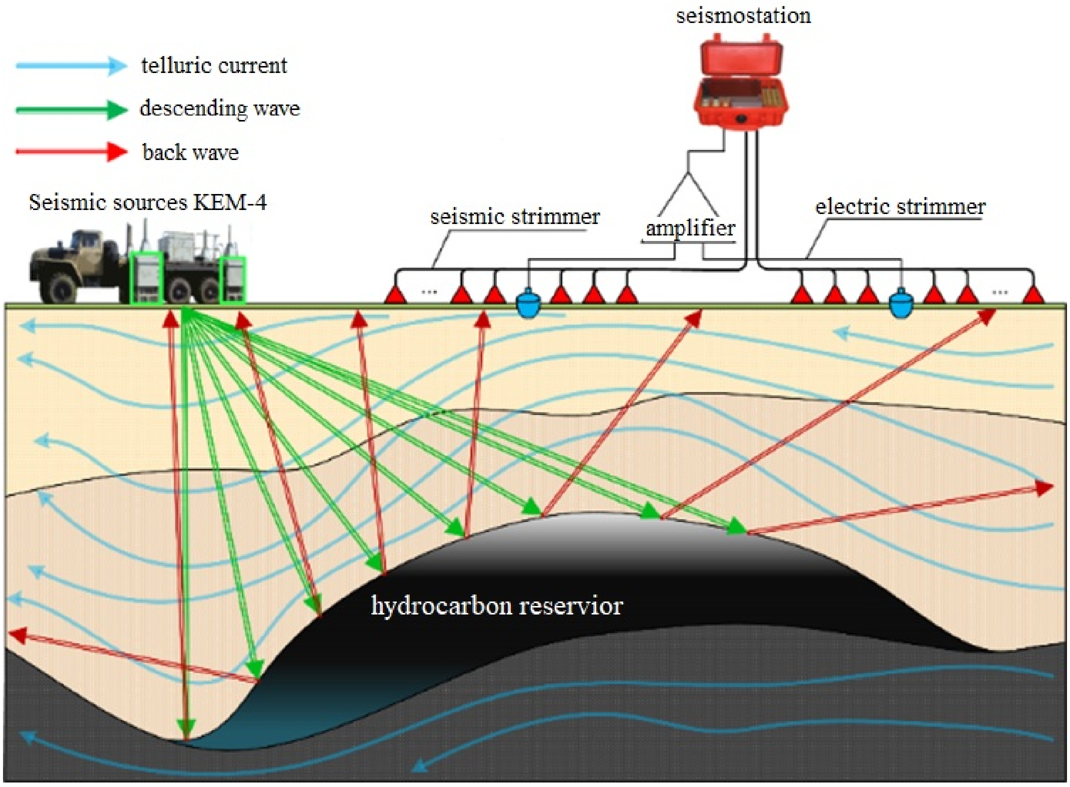

Fig.2 Measurement flowchart for standard prospecting seismology

The measurement scheme is given in Fig.2. The reflected seismic vibrations were recorded on a specialized seismic station (by Research and Production Company "SibGeofizPribor", OOO), which allows a multi-channel recording (24 channels) of seismic vibrations. Standard submersible geophones were used, the distance between which was 12.5 meters. The electromagnetic field was recorded using a 200-meter grounded electric dipole; standard non-polarizable reference electrodes were used for grounding. The dipole connected via a specialized bandpass amplifier (0.1 – 100 Hz) to a free input of the seismic station. This amplifier allows matching the resistances and suppresses a 50-Hz industrial noise by 40 dB.

Point A (Fig.1) has got the measurement results obtained by means of standard prospecting seismology, and observational data by the passive SE method [20], comparing them will enable a more accurate interpretation of the SEE. Comparison of the results obtained in 2015-2019 is necessary as it allows to evaluate the repeatability of the method and more accurately assess the SEE in this field.

To evaluate the seismoelectric effect, a cross-correlation function was used, with averaging over 24 seismic receivers and 3 different measurements. The final formula will be as follows:

$$R_{ES}(\tau)=\frac{1}{72}\cdot\sum_{M=1}^{3}\left(\sum_{N=1}^{24}\left(\int_{0}^{T}\overline{E}_{MN}(t)\cdot\overline{S}_{MN}(t-\tau)dt\right)\right) \quad (7)$$

where $\overline{E}_{MN}$ *(t)* and $\overline{S}_{MN}$ *(t)* are the signals received by the grounded electric dipole and seismic receivers; T is the time of recording the signals by the seismic station and is 6 sec.

3. RESULTS AND DISCUSSIONS

3 characteristics were obtained, corresponding to the axes of the seismic receiver (X, Y, Z), of the averaged cross-correlation functions. These characteristics are shown in Fig.3-5.

As can be seen from the charts, the accumulation allows identifying the peaks of the cross-correlation function of seismic and electric fields. The data of prospecting seismology, exploratory drilling and the experience of previous works [20,21] show that the productive anomaly is registered at 1.3 – 1.5-second signal delays, which is proven in Fig.3-5. Thus, at the moment the front of a seismic wave reaches the boundary of the productive formation, the maxima of the cross-correlation function are observed. The local maxima, apparently, are due to the structure of the sheet deposit itself and can bear additional informational components, which, when compared with 2D or 3D seismic surveys, can subsequently provide more accurate data for exploratory drilling.

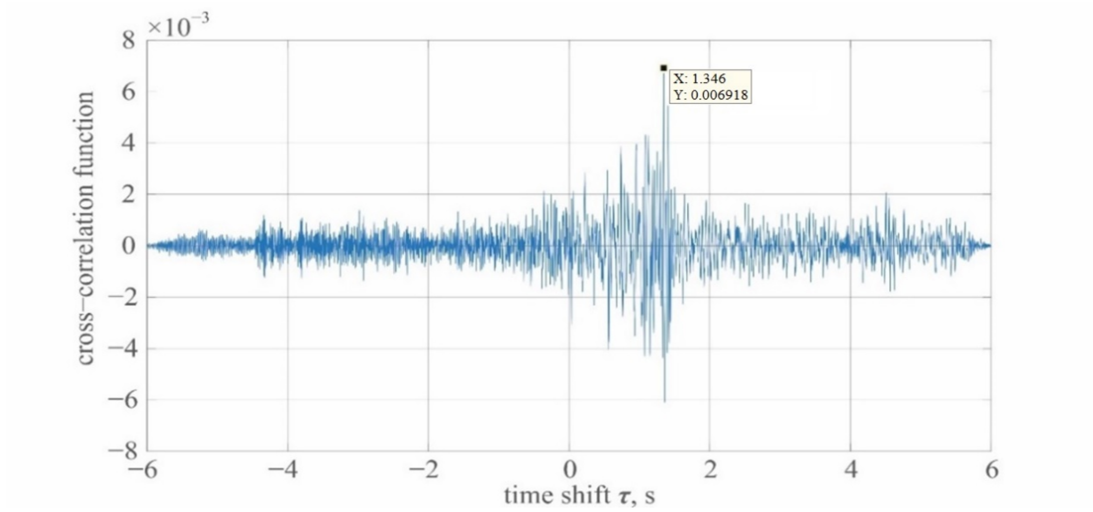

Fig.3 The averaged cross-correlation function for axis X

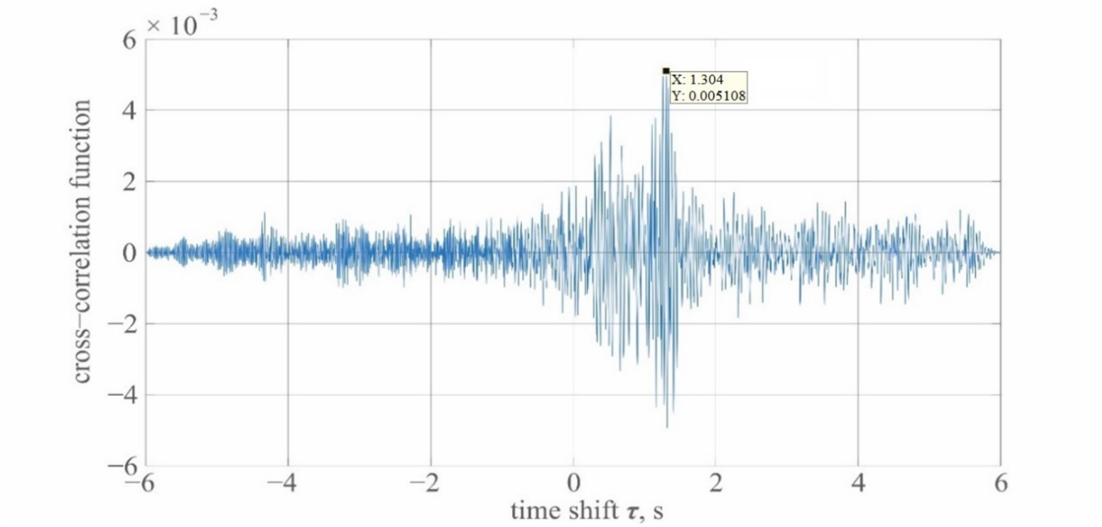

Fig.4 The averaged cross-correlation function for axis Y

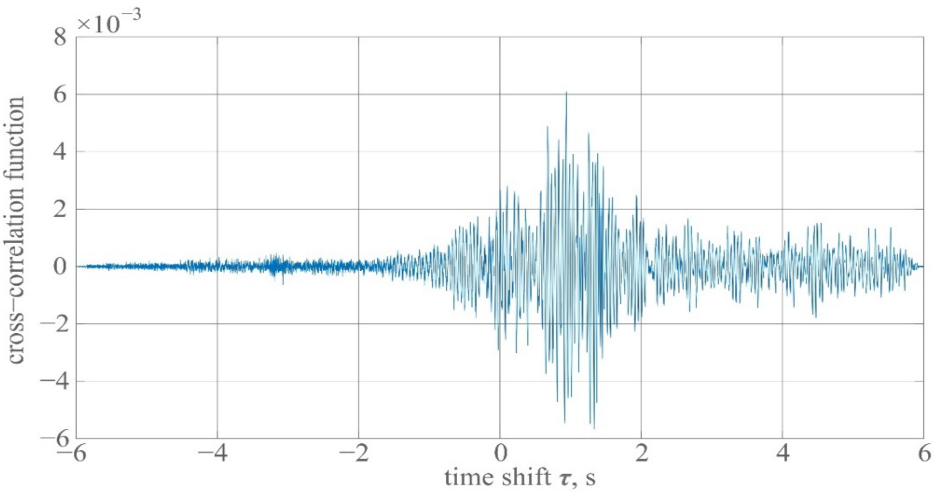

Fig.5 The averaged cross-correlation function for axis Z

The time of appearance of the peaks of the averaged cross-correlation functions for X, Y, and Z axes differs. This is explained by the fact that the P- and S-type waves propagate at different speeds, and the time of the hydrocarbon productive formation exposure to seismic wave will be different. The maxima of the cross-correlation function registered by means of averaging do not exceed the value of 0.01, which is consistent with the calculated data given in this paper and needs additional analysis and verification both in the experimental field and in the development and evaluation of the mathematical models.

Using correlation analysis and signal accumulation made it possible in this case to increase the total signal-to-noise ratio, but it is worth adding that the data were obtained only at one field and the statistics of observations at different fields with different geological and geophysical conditions are needed. In past works [20,21], observational data have already been cited, but with the use of much greater signal accumulation in the time domain. Here, due to the use of accumulation due to the number of geophones, it was possible to reduce the measurement time to 6-10 seconds.

4. CONCLUSION

The study provided in this paper shows that the recording of seismoelectric effects for the search for hydrocarbons is a challenging task, solving which requires the use of advanced highly-sensitive sensors for recording seismic and electromagnetic fields. The analysis of the level of the electromagnetic field created by a hydrocarbon pool, with the use of a mathematical model shows that the field level on the Earth’s surface can only be recorded using averaging or accumulation of the signals. In the case non-explosive sources of a seismic field, this problem is solved by accumulating the number of measurements and recording the signals by the required number of seismic receivers. It is worth taking into account that separating the seismic receivers too much in the space will introduce distortions in the information received. Thus, the use of the seismoelectric method to refine the data obtained during exploration works will scarcely increase the labour costs, but it can provide additional informational signs about the structure of the field. The authors of this paper believe that recording of seismoelectric effects for the search for hydrocarbons is a crucial task, solving which will increase the percentage of productive wells in the future.

According to the authors, this method of accumulation, that is, increasing the signal-to-noise ratio, is promising, since without additional hardware (except for an electrically grounded dipole), an additional informational sign can be obtained during exploration for hydrocarbons. The use of this kind of joint measurements will allow in the future to increase the reliability of exploration and the percentage of productive wells.

5. ACKNOWLEDGMENTS

The authors thank Siberian Federal University for providing their facilities to implement this project. This work has been done with the support of the Council on grants of the President of the Russian Federation (scholarships of the President of the Russian Federation to young scientists and graduate students No. 904.2018.1) and was funded by RFBR, the Government of Krasnoyarsk Krai and enterprise of Krasnoyarsk Krai according to the research project № 18-47-242017.

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